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REVISION OF STANDARDS FOR MEASUREMENTS OF SHIELDING EFFECTIVENESS OF ENCLOSURES

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REVISION OF STANDARDS FOR MEASUREMENTS OF SHIELDING EFFECTIVENESS OF ENCLOSURES

ABSTRACT

This report covers proposed revised standards for measurements of shielding effectiveness of enclosures as a result of a research program. The revised standard is a result of theoretical and experimental investigations attempting to improve military standard specification MIL-STD-285 for testing shielded enclosures in the frequency range of 100 kilocycles to 10,000 megacycles. The improved standard proposes to extend the low frequency end of the specification, and has been formulated in terms of tests at 15 kilocycles, at the lowest natural resonant frequency of the enclosure, and near nine kilo-megacycles. The reasons for choosing these frequencies are: (1) at the low frequencies, shielding against low-impedance fields is comparatively difficult; (2) at the mid-frequencies, enclosures exhibit resonances which can significantly affect the performance of the enclosure; and (3) at very high frequencies, shielded enclosures exhibit phenomena not predictable from their performance at the lower frequencies.

For the three frequency ranges, the respective methods of evaluating shielding enclosures follow:

(1) Two large rectangular transmitting loops surround and "immerse" the enclosure in an essentially magnetic field. An average value of the field penetrating the enclosure is obtained using a small pick-up loop in the center of the shielded enclosure. This method requires only one field measurement since the voltage induced in the pick-up loop without the enclosure may be obtained analytically. A small loop probe may also be used to explore the local fields in the neighborhood of wall and door joints.

(2) A half-wave dipole is used as the transmitting antenna outside the enclosure, and an electrically short (of the order of $\lambda/8$) dipole is used as the receiving antenna inside.

(3) A microwave source (such as a radar) is used to illuminate the shielded enclosure. The radar is located external to the enclosure under test, and its output is directed by means of a rectangular horn onto the enclosure. A microwave discone or rectangular horn is utilized as the receiving antenna inside.

All three tests utilize standard radio-interference meters with accessory equipment as detectors and standard signal generators of the appropriate frequency range as transmitters.

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REVISION OF STANDARDS FOR MEASUREMENTS OF SHIELDING EFFECTIVENESS OF ENCLOSURES

I. PURPOSE

The purpose of this program is to develop improved techniques for measuring the effectiveness of shielded enclosures in the frequency range of 14 kilocycles to 10,000 megacycles per second, and to provide recommendations for standard methods of evaluating such enclosures.

II. GENERAL FACTUAL DATA

A. Logbook and Contributing Personnel

The engineers who contributed to the work discussed in this report are:

Name	Title	Man-Hours to End of 4th Quarter	Man-Hours Total
R. B. Schulz	Research Engineer - Project Engineer	515	539
L. C. Peach	Research Engineer	803	835
D. P. Kanellakos	Assistant Engineer	956	1200
L. J. Greenstein	Technical Assistant	136	136
Additional Engineering Services		45	68

Data obtained on this project are contained in Logbooks C8375, C8724, C8836, and C8355.

B. References

The following references are closely related to the work presented in this report. These, in turn, contain additional references.

(1) "Revision of Standards for Attenuation Measurements of Shielded Enclosures", by L. C. Peach., Second Quarterly Progress Report, Contract No. NObsr-72824, January, 1959.

(2) "Revision of Standards for Attenuation Measurements of Shielded Enclosures", by L. C. Peach, Third Quarterly Progress Report, Contract No. NObsr-72824, April, 1959.

(3) "Revision of Standards for Measurements of Shielding Effectiveness of Enclosures", by D. P. Kanellakos, Fourth Quarterly Progress Report, Contract No. NObsr-72824, July, 1959.

(4) "New Techniques for Evaluating the Performance of Shielded Enclosures", by D. P. Kanellakos, L. C. Peach, R. B. Schulz, and A. P. Massey, Proceedings of the Fifth Conference on Radio Interference Reduction and Electronic Compatibility, Chicago, Illinois, October, 1959.

(5) "A Coaxial Device for Measuring the Performance of Shielding Materials", by D. P. Kanellakos, L. C. Peach, Proceedings of the Fifth Conference on Radio Interference Reduction and Electronic Compatibility, 1959.

(6) "Choice of Material for Electromagnetic Screening Rooms", by A. P. Yephemov, Radiotechnica, Vol. 13, No. 11, pp. 60-66, 1958 (in Russian).

C. Meetings and Conferences

Date. July 9, 1959

Place. Navy Department, Washington, D. C.

Personnel Attending:

Mr. L. W. Thomas, Bureau of Ships

Mr. A. P. Massey, Bureau of Ships

Mr. R. B. Schulz, Armour Research Foundation

During this meeting, Mr. R. B. Schulz reviewed the status of the project with Messrs. L. W. Thomas and A. P. Massey and presented suggestions for future work.

III. DETAILED FACTUAL DATA

A. Introduction

The Bureau of Ships, Department of the Navy, awarded Contract NObsr-72824 to the Foundation in order to obtain basic technical information which will form the basis for revision of present military standard specification MIL-STD-285 on techniques for measuring the performance of shielded enclosures. This revised specification for testing shielded enclosures is to furnish a maximum amount of information regarding the performance of the enclosure consistent with factors of equipment availability and measuring time.

Theoretical and experimental results obtained during the research program~~, which began 18 June 1958 and ended 30 September 1959,~~ indicate that tests should be performed in three frequency ranges: at 15 kilocycles, at the lowest natural resonant frequency of the enclosure, and near 9 kilo-megacycles. The proposed revised test standards which emerged out of the work performed during this program are given in subsequent sections of this report.

B. Proposed Revision of Standards for Measuring Shielded Effectiveness of Enclosures

1. Scope

This proposed standard covers a method of measuring the shielding characteristics of electromagnetic enclosures used for electronic test purposes over the frequency range from 14 kilocycles to 10,000 megacycles. Tests at approximately 15 kilocycles*, at the lowest natural resonant frequency of the

*The test frequency of 15 kilocycles is chosen rather than the lower end of 14 kilocycles because the lower frequency limit of the commonly available AN/URM-6 RI/FI detector is 14 kilocycles; thus the use of the very end of its frequency tuning range is avoided.

enclosure, and near nine kilomegacycles* are recommended. The respective reasons for picking these three tests are (1) the unique effects of magnetic fields at low frequencies, (2) the cavity resonance effects of the enclosure, enabling it to sustain standing waves in its interior at the intermediate frequencies, and (3) the effects of shield separation laterally (in the case of multiple layer enclosures), the effects of joints, and the effects of cell size of mesh and screening materials, since perforations and wires act as radiating dipoles at the higher frequencies.

2. Definitions of Measurement Terms

In the past, attempts have been made to measure shielding performance with regard to electromagnetic fields by field techniques analogous to conductive measurements of filter performance. In the case of electrical filters, both the concepts of "attenuation" and "insertion loss" are used.

An attenuation type of measurement expresses the ratio of output power delivered to a load to filter power input in db. Insertion loss expresses the ratio of output power delivered to a load, to power delivered when the filter has been replaced by direct connection of load to source, in db. In both cases, source and load impedances are specified, usually as 50 ohms. Since it is usually desirable to know the benefit derived from use of a filter (a "before" and "after" comparison), it is far more common to find filters described in terms of insertion loss than attenuation. This is true even though attenuation is independent of source impedance, whereas insertion loss is dependent upon it.

The analogous situation occurs in the case of elementary shielding theory, where a uniform plane wave is incident upon a planar conducting sheet of infinite extent. Measurements on opposite sides of the sheet can be used in

*A frequency of the X_S-band (9 to 9.6 kmc) was chosen and not the upper frequency of 10 kmc because of availability of equipment in this range.

a calculation of attenuation, whereas measurements on the side of the sheet away from the source, both in the presence and absence of the sheet can be used in an insertion loss calculation.

The actual shielding situation is, however, not that of an infinite sheet but a complete, finite, enclosure. In this case, the source and load impedances are no longer equal and the load impedance (due to reflections) is a complicated function of frequency. The insertion-loss type of measurement thus has less meaning since, not only is the shield inserted and removed during the measurement, but the equivalent load impedance is changed at the same time. In brief, the concepts that are useful for a uni-dimensional problem in lumped-constant circuits or elementary field theory appear to be of little merit in a three-dimensional electromagnetic field application.

Both the terms "attenuation" and "insertion loss" have been used quite loosely, often interchangeably, in the history of shielding measurements. Since neither term is truly descriptive of the type of measurement proposed herein, another term is being employed. This term is called "shielding effectiveness".

The shielding effectiveness S is defined as a ratio of electric or magnetic fields, expressed in db, which is related to the powers received at a point in space contained by a shielding enclosure in the absence and presence of the enclosure, respectively. As used in this analysis, shielding effectiveness is the figure of merit for electromagnetic shielded enclosures. Thus,

$$S = 20 \log \frac{H_1}{H_2} \quad \text{for the 15 kc test} \tag{1a}$$

and

$$S = 20 \log \frac{E_1}{E_2} \quad \text{for the lowest natural resonant frequency and nine kmc tests} \tag{1b}$$

where, at the measurement location, H_1 and E_1 are the magnitudes of the magnetic and electric fields, respectively, in the absence of the enclosure; and H_2 and E_2 are the magnitudes of the magnetic and electric fields, respectively, in the presence of the enclosure. The magnetic field components only will be measured for the 15 kc (low-frequency) test and the electric field components only for the other two tests, as shown in Eq. (1a) and (1b) respectively. Since the impedances involved are dissimilar in the absence and presence of the enclosure, shielding effectiveness is not a true power ratio, but is used for the sake of convenience as a figure of merit.

3. Requirements

a. Test Equipment

The test equipments necessary for the performance of each test are summarized in Table I. Applications of these equipments are described in detail when the measurement procedures are discussed.

b. Test Set-up

The arrangement of signal sources, measuring equipment, and pick-up devices with respect to the shielded enclosure under test is specified in the following paragraphs. In all cases, it is intended that all RF cables, power line filters, power lines, and other cables which will normally enter the shielded enclosure be in place when tests are conducted. The enclosure shall be inspected visually for any indication of leakage in the vicinity of utility entrances, doors, access panels, and joints, and to correct obvious defects of this nature before proceeding with measurements. Contact surfaces of panels should be cleaned and tightened, if necessary.

In the case of the low- and high-frequency tests, miscellaneous equipment, work tables, etc., may be left inside the enclosure. For the mid-frequency test, however, the enclosure shall be cleared of all objects not directly related to the test.

TABLE I - SUMMARY OF EQUIPMENT NECESSARY TO PERFORM SHIELDING EFFECTIVENESS TESTS

TEST FREQUENCY	SIGNAL GENERATOR	TRANSMITTING ANTENNA	RECEIVING ANTENNA	DETECTOR	ACCESSORIES (Not All Necessary at Same Time)
15 kc.	Audio Signal Generator capable of providing detectable output at frequency of test.	Two 10-Turn Loops encircling the enclosure. Each loop is made of No. 18 AWG insulated wire. Loops are placed near top and bottom horizontal planes of enclosure, and connected in series aiding by twisted leads. (See Fig. 1).	Antenna AT-205/URM-6, or One-Foot Diameter, 10-Turn Loop made of No. 12 AWG enamel insulated wire. Antenna AT-207/URM-6 (Loop Probe).	RI/FI Meter AN/URM-6 with meter accessories or High Input Impedance A.C. Voltmeter (plus low noise, narrow band-pass amplifier, if required.	Means of supporting transmitting loops. Tripod to support receiving antenna. Twisted leads. A. F. Ammeter or Voltmeter. Impedance matching transformer. A one-ohm non-inductive resistor.
Lowest Natural Resonant Frequency $f=150\sqrt{\frac{1}{\ell^2}+\frac{1}{\ell^2}}$ (See Fig. 3)	VHF Signal Generator capable of providing detectable output at frequency of test.	Antenna AB-371/U adjusted to a length $\ell_2 = 0.5\lambda$, placed on tripod CADV-10545 outside the enclosure at least 1.5λ away from largest wall, oriented perpendicular to wall and colinear with receiving antenna.	Antenna AB-371/U adjusted to a length $\ell_1 \leq 0.125\lambda$, placed on tripod CADV-10545 in the geometrical center of the enclosure, oriented perpendicular to largest side wall of the enclosure.	RI/FI Meter AN/URM-47 with meter accessories.	A shielded case constructed similar to a shielded room to protect detector from case leakage. Connecting RG-9B/U coax cables. Cable from feed-through connector to meter shall be as short as possible and provided with an additional shield. A coaxial short for case leakage tests.
X_S-band Frequency (9 to 9.6 kmc.)	X_S-band Radar Source capable of providing adequate output at frequency of test.	Rectangular X-band Standard Gain Horn Antenna, placed at least 5 feet away from any point of wall, oriented perpendicular to the wall and colinear with receiving antenna.	Antenna AT-570/URM, or Rectangular X-band Standard Gain Horn Antenna, placed at the center of the enclosure and oriented perpendicular to the wall. Polarization planes of the transmitting and receiving antennas should be the same.	RI/FI Meter IM-103 URM-42 with meter accessories and TN-131/APR-9 tuning head or X-band Spectrum Analyzer with accessories.	Directional coupler. Coax-to-waveguide coupler. Constant and variable waveguide attenuators. Transmission line RG-9B/U coax cables. Dummy load.

4. Low-Frequency Tests

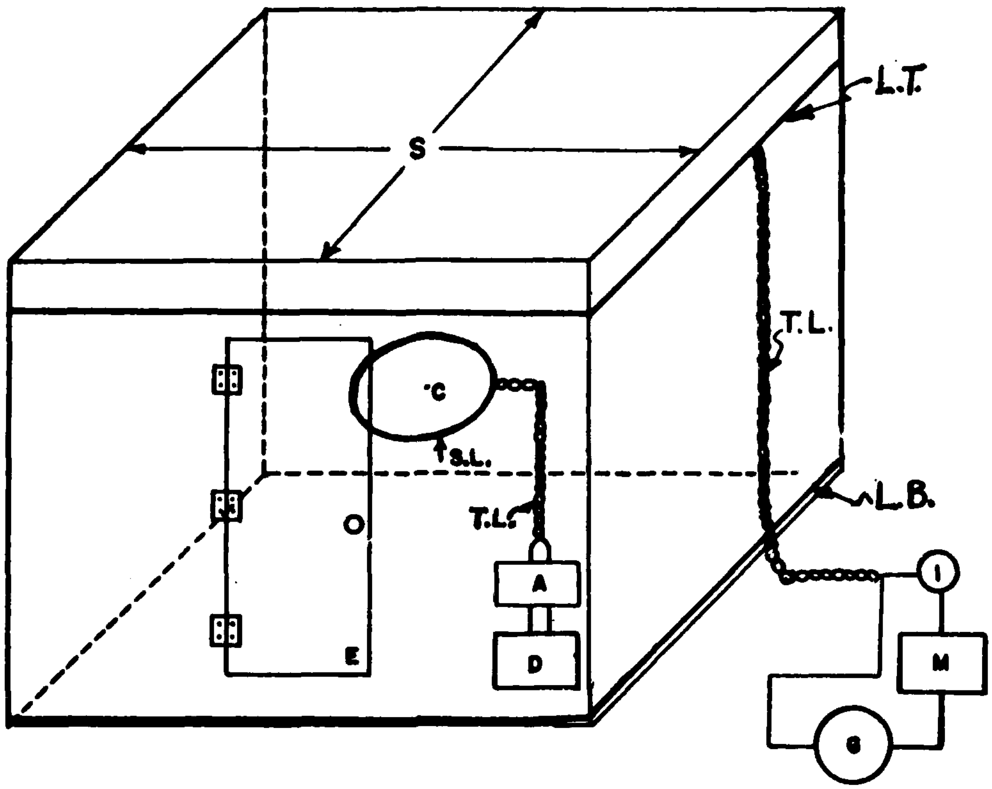
a. Introduction

Since the presence of low-impedance fields at low frequencies is fairly common, and since these fields are the most difficult to shield against, the low-frequency shielding effectiveness of an enclosure should be measured against low-impedance (essentially magnetic) fields. These low-impedance fields can most easily be produced by current loops whose dimensions are small compared to the wavelength. The method for producing low-impedance magnetic fields for testing the shielded enclosure utilizes two large, horizontal, rectangular loops completely surrounding the enclosure and located near the ceiling and floor of the enclosure, respectively. When a moderate current flows in the turns of the loops, it produces a magnetic field which completely immerses the shielded enclosure, and is sufficiently strong to permit making the required measurement with standard detection instrumentation.

b. Measurement of Shielding Effectiveness

Refer to Fig. 1. The two loops L. T. and L. B. shall be placed in parallel horizontal planes equally near the roof and floor of the enclosure, so that they do not hinder the opening and closing of the enclosure entrance E. Each loop shall consist of 10 turns of No. 18 insulated wire which are wound directly on the outer enclosure wall S. The two loops shall be connected in series aiding with twisted leads T. L., and shall be connected to an audio signal generator tunable to 15 kc, such as the Hewlett-Packard model 205AG.

An impedance-matching transformer M may be used, if necessary, to match the output impedance of the generator to that of the external loops. The impedance of the latter can be measured in its final test position with an a.c. impedance bridge at the frequency of test. The current flowing in the turns of the loop shall be measured with an a.c. ammeter I or the voltage across a one



Frequency of test: 15 kc.

C	= Center of shielded enclosure	E	= Enclosure entrance
S	= Outer shielding layer	T.L.	= Twisted leads

L. T. = Top loop } Each 10 turns of No. 18 insulated wire horizontally oriented
L. B. = Bottom loop } and engulfing the entire enclosure. (Transmitting antenna)

S.L. = Circular loop. Antenna AT-205/URM-6 used in conjunction with Radio Interference - Field Intensity meter AN/URM-6, or 10-turn, 12-inch diameter loop of No. 12 AWG copper enameled insulated wire. Placed in the center of the room midway between L. T. and L. B. (Receiving Antenna)

G = Low impedance signal source to obtain adequate output at the frequency of test, such as Hewlett-Packard Model 205 AG.

I = Audio frequency A. C. ammeter satisfactory at 15 kc. (Instead of a measurement of current directly, the voltage across a 1-ohm non-inductive resistor may be measured to find the current.)

M = Impedance matching transformer, if necessary.

D = Radio Interference Set AN/URM-6 or high input impedance A. C. voltmeter such as Hewlett-Packard Model 400 D.

A = Low noise, narrow bandpass amplifier, if necessary (not required for use with AN/URM-6).

FIG. 1 SHIELDING EFFECTIVENESS MEASUREMENT - LOW IMPEDANCE FIELDS

ohm non-inductive resistor may be measured.

While the loops are in the positions shown in Fig. 1, a small loop probe shall be used to search for leaks and other imperfections that could be present in the enclosure. The small probe shall be a multiturn unit AN-207/URM-6 used in conjunction with an AN/URM-6 Radio Interference-Field Intensity Meter, or equivalent. When the small loop probe is carried in a horizontal plane around the enclosure walls, a variation of the pick-up voltage may resemble the illustration given in Fig. 2. The joints shall be cleaned for good electrical contact, and tightened until the leakage peaks are reduced to a minimum before the low-frequency test of shielding effectiveness is performed.

The magnetic field intensity, H_1 produced at the center of the room, but without the presence of the shielded enclosure, under the conditions described earlier shall be calculated theoretically from

$$H_1 = \frac{2\,N\,I\,ab}{\pi} \frac{1}{\sqrt{a^2 + b^2 + d^2}} \left\{ \frac{1}{a^2 + d^2} + \frac{1}{b^2 + d^2} \right\} \qquad (2)$$

N = number of turns in each of large loops (= 10)

I = current in amperes in large loops

2a = x-dimension of larger loop in meters

2b = y-dimension of large loop in meters

2d = separation of the two large loops, center-to-center, in meters.

At the geometrical center of the enclosure shall be placed a pick-up loop S.L. similar to antenna AT-205/URM-6 or, alternatively, a 10 turn, 12-inch diameter pick-up loop of enamel-insulated wire. The plane of the pick-up loop shall be parallel to the planes containing L. T. and L.B. The output of the signal generator G is then adjusted until a sufficient current I flows in the turns of the large outside loops 'nduce a measurable voltage in

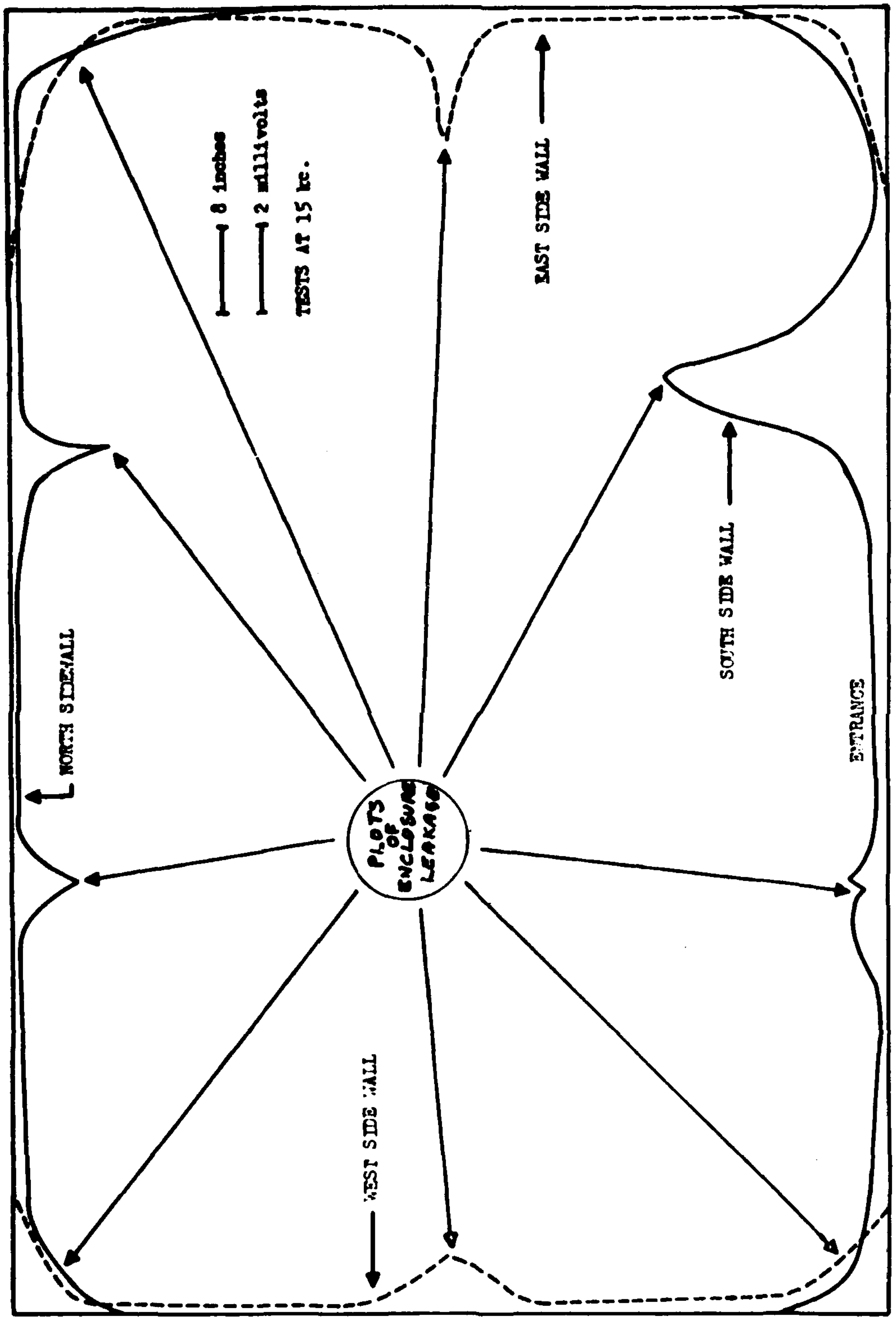


FIG. 2 PLAN VIEW OF SHIELDED ENCLOSURE SHOWING LEAKY JOINTS

the small inside loop. The voltage V_2 induced in the small loop at the center of the room shall be measured with the calibrated Radio Test Set AN/URM-6 or, alternatively, with a high-impedance voltmeter. The high-impedance voltmeter limits the current flowing in the small inside loop to a minimum. (This current should be essentially zero* since, if it were not zero, it would create an additional magnetic field which would tend to cancel those produced by the large loops and thus introduce an error in the measurement). A low noise, narrow band 15 kc amplifier A with a high input impedance may be used when the output signal of the small loop is insufficient to give a reading directly at the detector D. A test shall be made to assure that no case leakage exists at the detector D. It shall show no indication above the inherent background noise when the pick-up loop is disconnected from its input terminals while the generator G is connected to the transmitting antenna and supplying a current I.

For the AN/URM-6 detector, the magnetic field intensity H_2 at the center of the enclosure is given by the expression

$$H_2 = \frac{E_{eq}}{120\pi} \tag{3}$$

where E_{eq}** in volts per meter is the equivalent electric field intensity obtained as a measurement of the magnetic component. Since the shielding effectiveness S is given by the defining expression

$$S(db) = 20 \log \frac{H_1}{H_2}\ , \tag{4}$$

it may also be given for the AN/URM-6 as

*The AN/URM-6 meter actually has a low input impedance but the calibration of the instrument accounts for the field produced by loop current flow.

** E_{eq} is the corrected reading obtained on the AN/URM-6 meter. For correction and calibration factors that convert the microvolt reading to field intensity in microvolts per meter, refer to its calibration chart. Then multiply by 10^{-6} to obtain Eeq in volts per meter.

$$S(\text{db}) = 20 \log \left\{ \frac{2.40 \times 10^3 I}{E_{eq}} \frac{ab}{\sqrt{a^2 + b^2 + d^2}} \left(\frac{1}{a^2 + d^2} + \frac{1}{b^2 + d^2} \right) \right\} \quad (5)$$

For the high-impedance voltmeter detector, the magnetic field intensity H_2 at the center of the enclosure is given by

$$H_2 = \frac{V_{induced}}{2\pi f \; N_1 A \; \mu_o} \quad (6)$$

where

$V_{induced}$ = induced voltage in volts

f = frequency of test = 15×10^3 cps

N_1 = number of terms of small pickup loop = 10

A = area of 10-turn, 12-inch pick-up loop in square meters = 7.17×10^{-2} m^2

μ_o = permeability of free space = $4\pi \times 10^{-7}$ henry/meters

Then,

$$H_2 = 11.8 \; V_{induced} \quad (7)$$

and the shielding effectiveness S is

$$S(\text{db}) = 20 \log \left\{ \frac{0.540 I}{V_{induced}} \frac{ab}{\sqrt{a^2 + b^2 + d^2}} \left(\frac{1}{a^2 + d^2} + \frac{1}{b^2 + d^2} \right) \right\} \quad (8)$$

5. Measurements at Mid-Frequencies

a. Introduction

A rectangular parallelepiped shielding enclosure acts as a resonant cavity at the frequencies for which its dimensions are sufficiently large compared to a wavelength, and high standing waves can be sustained. The existing standing waves inside the "cavity" can affect any electrical equipment in an unfavorable manner whenever they are placed at locations where the field intensity is high because of resonance.

Resonance in a rectangular cavity occurs when

$$\ell = n \frac{\lambda_g}{2}, \tag{9}$$

where

ℓ = length of the cavity resonator

λ_g = the guide wavelength of resonator

n = an integer.

Eq. (9) holds for the natural resonance frequencies of the (m, n, p) mode

$$f_{mnp} = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{\ell}\right)^2}, \tag{10}$$

where

f_{mnp} is the natural resonant frequency in cycles per second

c = speed of light in vacuum, meters/second

a = width of cavity in meters,

b = height of cavity in meters,

ℓ = length of cavity in meters,

and where no two of the integers, m, n, or p may be zero simultaneously. The lower natural resonant frequency of the enclosure considered as a cavity is, from Eq. (10) above,

$$f = 150 \sqrt{\frac{1}{b^2} + \frac{1}{\ell^2}} \text{ megacycles}, \tag{11}$$

where b and ℓ are the dimensions of the largest side wall in meters. Figure 3 gives the lowest natural resonant frequency of a rectangular enclosure as a function of the two larger sides b and ℓ in meters.

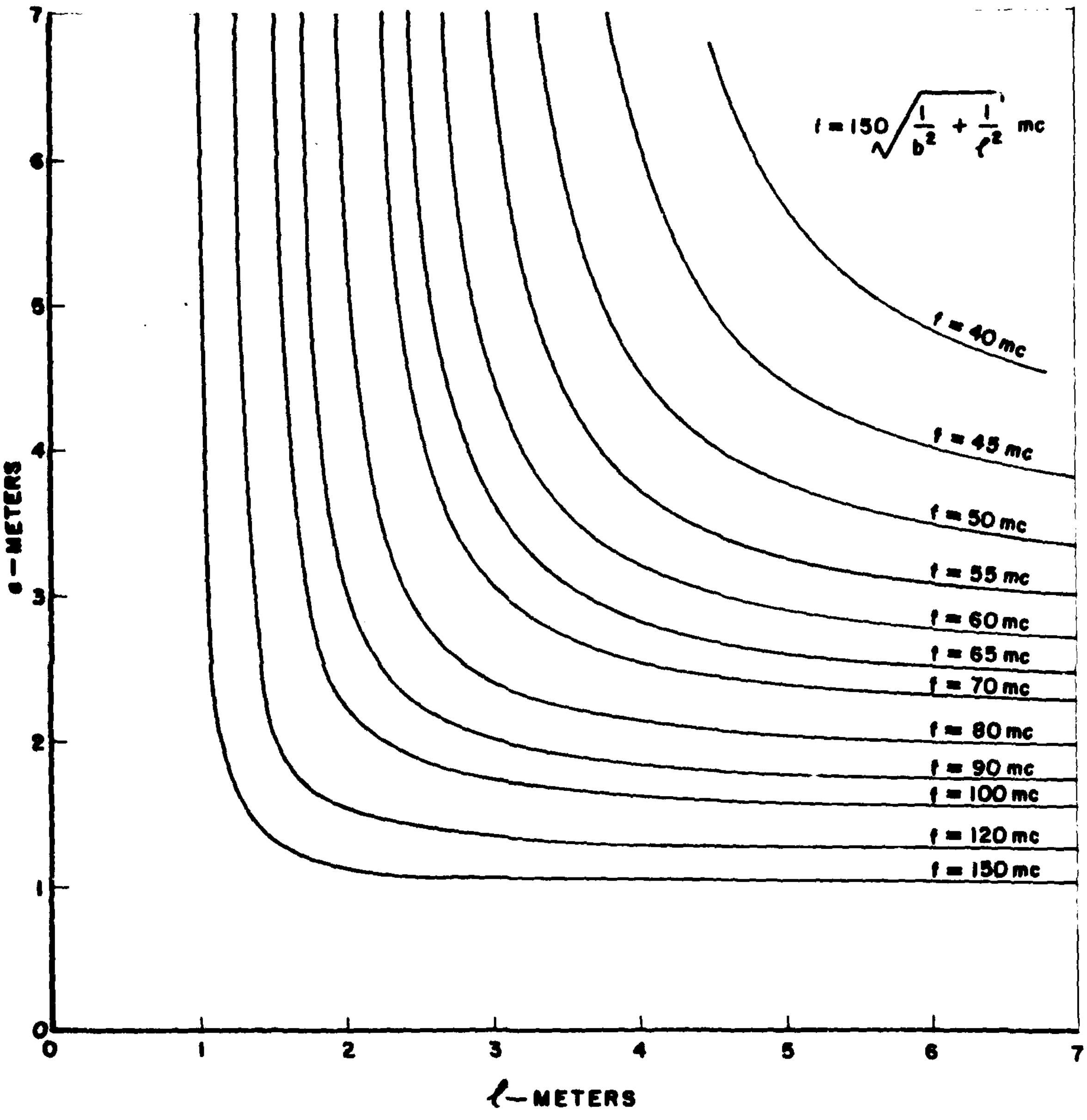


FIG. 3 LOWEST NATURAL RESONANT FREQUENCY CHART

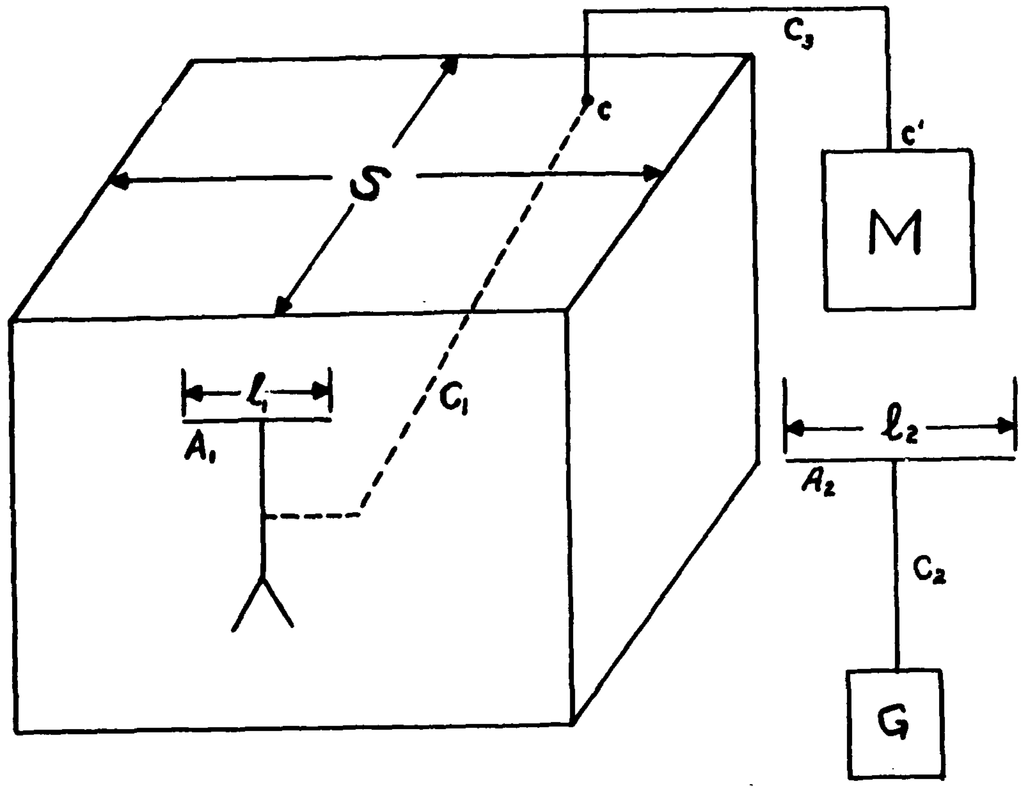
The resonance is difficult to find because the Q of shielded enclosure acting as a cavity is very high. With the calculated resonant frequency as a guide, measurements shall be made of the fields existing inside the room.

b. Measurement of Shielding Effectiveness

The measurement of shielding effectiveness at mid-frequencies is accomplished by using the measurement setup shown in Fig. 4. Because of the high attenuation introduced by the shielded enclosure at the mid-frequency region, a high-power signal generator, such as a Rollin Power Type Signal Generator, Model 30A, or equivalent, must be used. The generator shall feed a half-wave (at the frequency of test) dipole antenna A_2 through a 50-ohm double shielded cable (RG-9B/U) C_2; the antenna A_2 then produces in the vicinity of the enclosure free-field waves whose impedance is that of a plane wave. Inside the enclosure, at its center, another dipole antenna A_1 should be placed whose length ℓ_1 must be much less than a quarter wavelength at the frequency of test. The overall length of the dipole receiving antenna must be kept electrically short ($\ell_1 \leq \frac{\lambda}{8}$) so that (a) its impedance will not change appreciably as the frequency sweeps past the resonance frequency during measurements and (b) its impedance does not change when the antenna is taken outside the enclosure.

The antenna A_1 inside the shielded enclosure may be supported by its tripod. For the lowest natural resonant frequency, the electric field intensity is maximum at the center of the enclosure and its polarization is perpendicular to the plane of the larger side wall.

The output of antenna A_1 shall be brought outside the enclosure to an IM-88/URM-47 Radio Interference/Field Intensity Meter through a coaxial feed-through connector located in the roof or side wall of the enclosure. In



S = Enclosure shielding layers

G = High Power Generator suitable to obtain adequate output at the frequency of test. Rollin power type signal generator Model 3A or equivalent

A_2 = Transmitting Half-Wave Dipole Antenna, AB-371/U placed on tripod CADV-10545, $\ell_2 = \lambda/2$

A_1 = Receiving Electrically Short Dipole Antenna, AB-371/U placed on tripod CADV-10545, $\ell_1 \leq \lambda/8$

M = RI/FI Meter, AN/URM-47, in shielded case, with accessories

C_1, C_2, C_3 = RB-9B/U shielded coaxial cables

Frequency of test: The lowest natural resonant frequency of the enclosure considered as a cavity. In the case of a rectangular parallelepiped enclosure the frequency is

$$f = 150\sqrt{\frac{1}{b^2} + \frac{1}{\ell^2}} \text{ megacycles}$$

Where b and ℓ are the inside dimensions of the edges which form the larger side wall of the enclosure, expressed in meters.

FIG. 4 SHIELDING EFFECTIVENESS MEASUREMENT - MID-FREQUENCIES

order to minimize unwanted pick-up, cable C_3 (RB-9B/U) must be kept as short as possible.

The RI/FI meter shall be inserted in a shielded case to eliminate case leakage. Cable C_3 shall be provided with an additional third shield which is grounded to connector shells on both ends. When the connectors C or C' are shorted out, (see Fig. 4) the meter shall show no indication of any stray field pickup when the generator is turned on and off.

The transmitting antenna A_2 shall be oriented perpendicular to the center of the largest wall of the enclosure; this orientation will favor the lowest mode of excitation (TE_{011}). It should be separated from the enclosure until a maximum indication is obtained at the meter M. This distance of the center of the antenna A_2 from the enclosure wall corresponds to an integral multiple of half wavelengths ($n \frac{\lambda}{2}$). However, to prevent interaction of A_2 with the enclosure walls, n should be kept greater than 3. The generator frequency shall be varied in very small steps around the resonant frequency and a curve shall be plotted similar to the one which appears in Fig. 5. For certain shielded enclosures only the lower part of the curve might be detectable.

The coupling of the antennas A_1 and A_2 shall also be measured outside the enclosure when spaced the same distance and oriented the same way as when one was inside and the other outside. The measure of shielding effectiveness at the lowest natural resonant frequency is taken as the increase in attenuation of the calibrated attenuator in the output circuit of the generator G to give the same reading indication of the meter M that existed for reception through the enclosure shield.

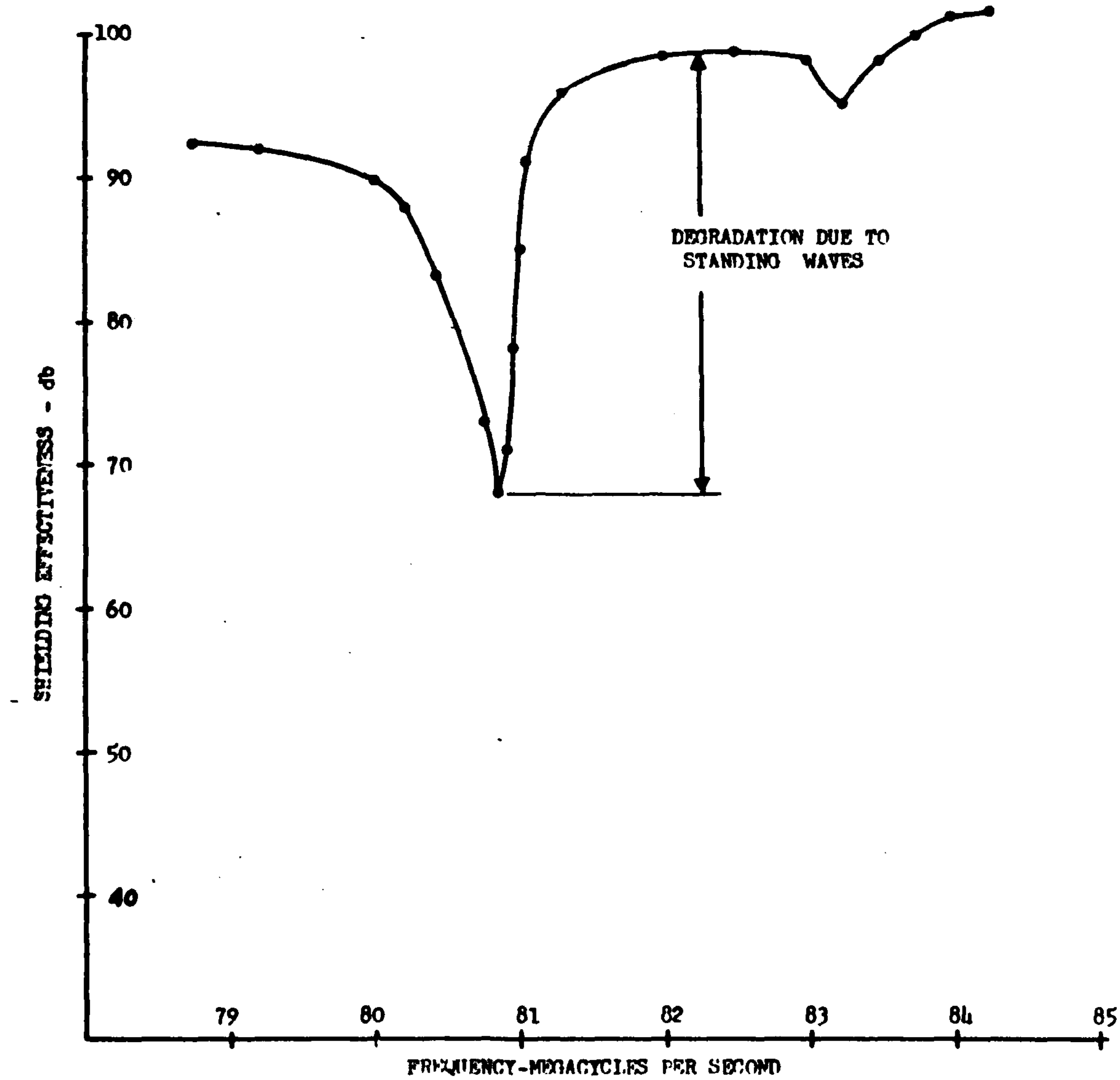


FIG. 5 VARIATION OF SHIELDING EFFECTIVENESS OF CELL-TYPE ENCLOSURE NEAR THE LOWEST NATURAL RESONANT FREQUENCY

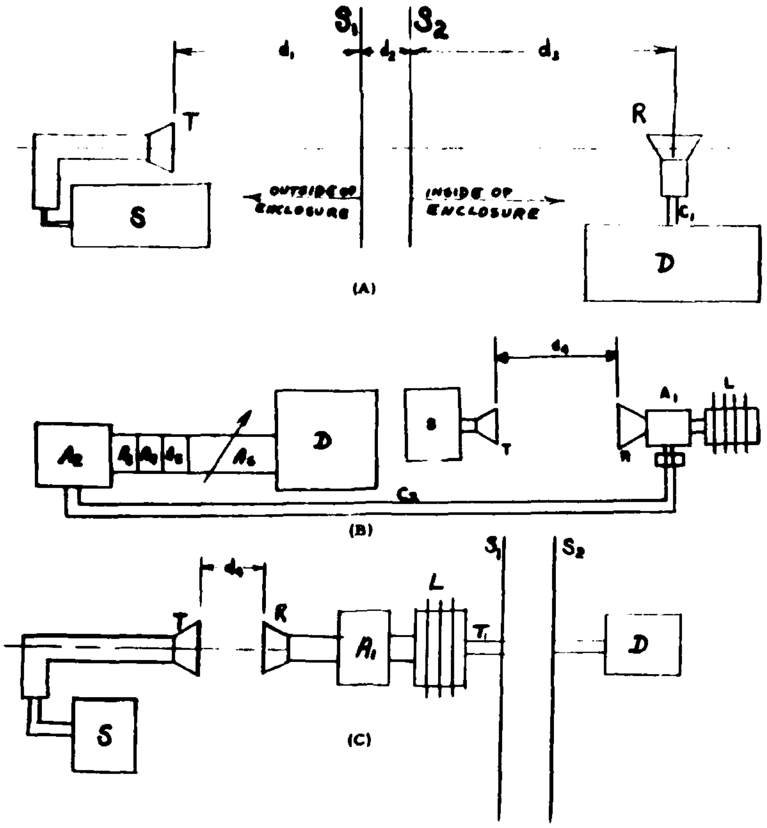
6. Measurements at Microwave Frequencies

a. Introduction

The electrical parameters ϵ, μ, and σ of shielding materials change with frequency. Since the reflection and attenuation losses, and therefore the shielding effectiveness, depend on these parameters, as well as on inter-panel contact resistances, a test of the performance of the shielded enclosure at high frequencies is necessary. The shielding effectiveness is very much affected by both the spacing between shields (in the case of multiple-shielded enclosures) and the spacing and size of the perforations in screening materials used. The space between shields can support high standing waves whenever the spacing is equal to $n\frac{\lambda}{2}$, where λ is the wavelength and n is an integer; this situation can theoretically bring about a 3 db decrease in shielding effectiveness below the value of a single screen wall. The radiating antenna should be kept sufficiently far from the enclosure wall (1) to prevent the former's radiation pattern from being changed appreciably, and (2) to keep to a minimum the amount of reflected energy feeding back into the horn and thus protect the source (normally a magnetron). This distance should be at least five feet.

b. Measurement of Shielding Effectiveness

Refer to Fig. 6. The measure of shielding effectiveness for the enclosure is taken as the increase in the db setting of the attenuator used in the output of the detector D to obtain the same reference level in the detector when the enclosure walls S_1 and S_2 are removed. Because the strong field generated by T may penetrate the cases of detector D, the attenuators, or the transmission line cables C, these equipment shall be placed away from the direct path of the transmitting antenna T or its reflections as is shown in Fig. 6(B). The distance between the receiving and transmitting antennas is maintained fixed.



(A) - SHIELDING EFFECTIVENESS MEASUREMENT

(B) - MEASUREMENT OUTSIDE.
EQUIPMENT OUTSIDE ENCLOSURE.

(C) - MEASUREMENT OUTSIDE.
EQUIPMENT LEFT INSIDE ENCLOSURE.

$d_1 > 5$ feet — S_1 = Outer Shield

d_2 = normally one or two inches — S_2 = Inner Shield

d_3 = Distance from S_2 to center of enclosure — $d_4 = d_1 + d_2 + d_3$

S = Radar Signal Source suitable to obtain adequate output at the frequency

f = frequency of test: an X_s-band frequency (9 to 9.6 kmc.)

D = AN/URM-42 with TN-131 tuning head or detector of adequate sensitivity, tuned to the frequency of test and used either as a calibrated detector or as an equal-reference-level indicator.

T = Transmitting X_s-band standard gain horn antenna

R = Receiving Antenna Horn, such as AT-570/URM or standard gain horn

A_1 = Directional Coupler, calibrated in db loss at the frequency of test

A_2 = Coax to Waveguide Coupler, calibrated in db loss at the frequency of test

A_3, A_4, A_5 = Constant Waveguide Attenuators, calibrated in db loss at the frequency of test

A_6 = Variable Waveguide Attenuator, calibrated in db loss at the frequency of test

C_1, C_2 = Transmission Line Cable, RG-9B/U, calibrated in db loss at the frequency of test

T_1 = Transmission Line Connector bonded to both S_1 and S_2

L = Dummy load: X912A may be used.

FIG. 6 SHIELDING EFFECTIVENESS MEASUREMENTS - MICROWAVE FREQUENCIES

The position of the transmitting antenna with respect to the enclosure shall be anywhere around the enclosure and in any orientation to the panel seams, door, etc., but perpendicular to the wall and not near a corner. At any one point, the shielding effectiveness will be a maximum if the distance between shields of a multiple shielded enclosure is equal to $\frac{(2n+1)}{4}\lambda$, and a minimum if the distance is equal to $\frac{n}{2}\lambda$. These two distances represent small variations in the nominal one-or two-inch separation* of the two shields. Measurements may be made at one point and the two shielding layers, if non-rigid, may be pulled slightly apart or pushed slightly together. Both maximum and minimum attenuations shall be recorded.

A test must be made to assure that no leakage exists at D, A, or cables C_1 and C_2. The detector should show no indication above inherent background noise when cable C_1 or C_2 is disconnected and the end is capped, and should show no indication as the transmitter is turned on and off, when a metallic plate is placed up against R to completely cover the horn antenna.

If D shows no indication above inherent receiver background when the receiving antenna is inside the enclosure, the db increase in attenuation to obtain receiver background when the receiving antenna is placed outside the enclosure will indicate that the shielding effectiveness is at least the insisted amount of attenuation and the signal source S is not sufficiently strong or the detector D is not sensitive enought for a full measurement.

Signal source S is a generator of sufficient power output. Typical sources may be a radar or any other X_S-band source of adequate output to obtain readings.

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*Notice that the effective separation in terms of wavelength changes with frequency.

The attenuators, couplers, and cables (A_1, A_2, A_3, A_4, A_5, A_6, and C_1 or C_2) used are connected in series and shall have been previously calibrated at the frequency of test. The directional coupler A_1 and dummy load L are used to obtain a decrease in the signal source before it is fed directly into the waveguide attenuators in order not to exceed in average power the attenuator ratings. When tests are made with the enclosure wall in place, (Fig. 6C), the directional coupler A_1, coaxial-to-waveguide coupler A_2, and cable C_1 are to be removed and R is to be connected directly to the waveguide attenuators. The attenuators used must have a total attenuation in db at least as high as the shielding effectiveness of the enclosure and the total inserted attenuation taken into account.

The detector used may be an AN/URM-42 with TN-131-APR-9 tuning head, an ST-U3A Polarad Spectrum Analyzer, or equivalent on which the lowest readable level shall be used as a reference level indicator.

C. Experiments Performed at High Frequencies During Last Quarter

The setup shown in Fig. 7 was used to test the enclosure at high frequencies during the previous quarterly period. The output of the AN/APS-25 radar was directed by means of a rectangular horn onto the screening material. The radar microwave energy source was located outside the enclosure. The distance d_1 from the outer enclosure wall to the face of the transmitting antenna was used to (1) protect the radar from excessive amounts of reflected power and (2) to produce a uniform illumination of the wall. Inside the enclosure, an IM-103/URM-42 RI/FI meter with its accessories was used, as depicted in Fig. 7. The coupling between the two antennas was measured in the presence and absence of the enclosure. The db change in attenuation to obtain the same reading in the receiver was the measure of the shielding effectiveness of the enclosure.

For one cell-type enclosure of old manufacture, the shielding effectiveness was found to be only 30 db. This value was reduced to 20 db when the separation of the two shields was pushed slightly together or pulled apart from their static positions. Because of the low shielding effectiveness of the above enclosure, it was difficult to detect a variation in effectiveness near a joint. When the enclosure door was not closed tightly by means of the two door handles, the decrease in shielding effectiveness was about 15 db. The extremely low shielding effectiveness of the enclosure can be attributed partly to the corrosion formed at the joints; the leakage at corroded joints can be expected to increase with frequency.

IV. CONCLUSIONS

A standard for testing electromagnetic enclosures has been presented based on theoretical and experimental investigations. The standard, it is

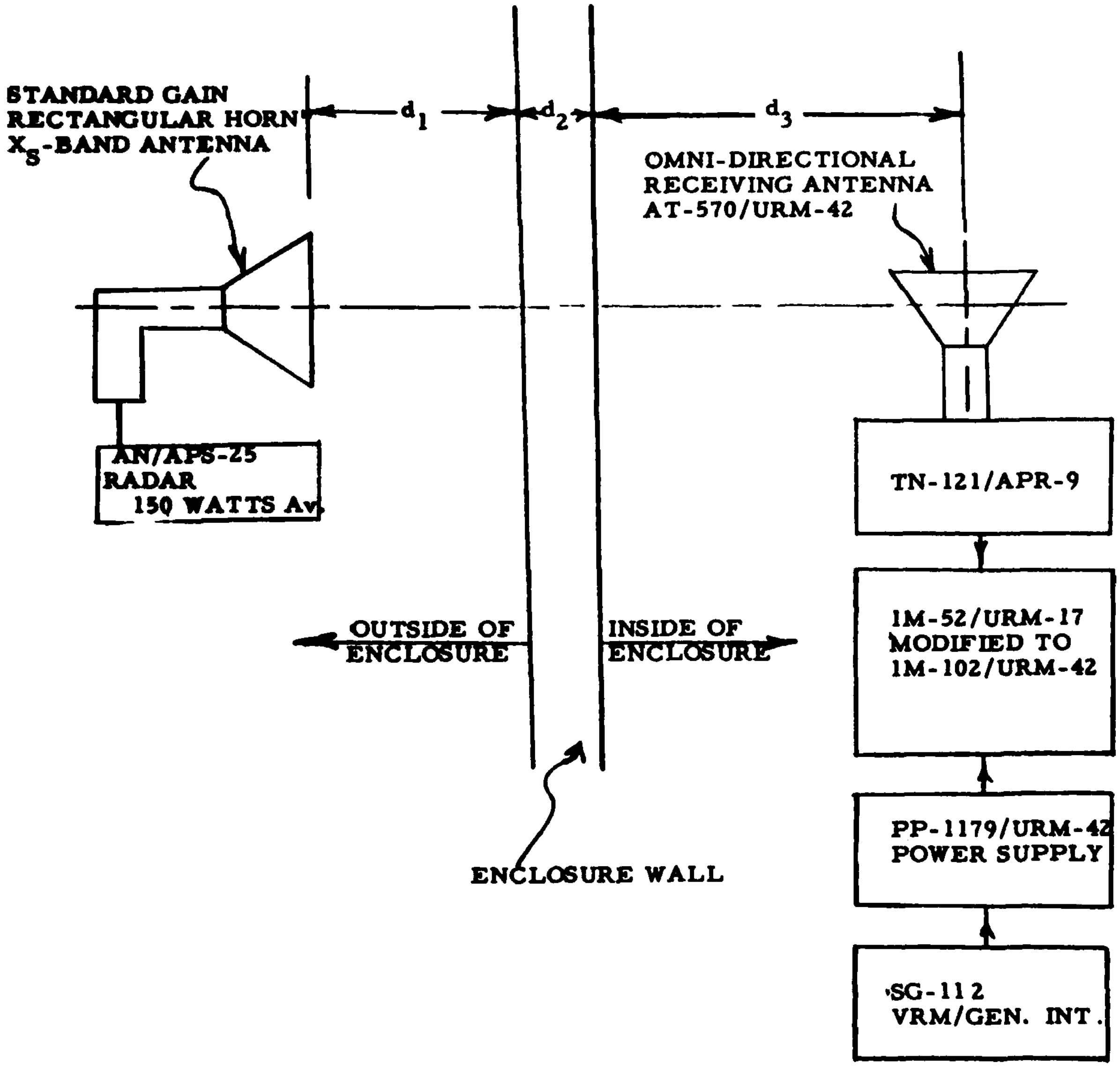

FIG. 7 SHIELDING EFFECTIVENESS MEASUREMENT - HIGH FREQUENCIES

believed, is an improvement over the current military standard specification MIL-STD-285 dated June 1956, since it furr.shes a maximum amount of information regarding the performance of the enclosure without requiring an undue amount of test equipment and effort. One man can perform all three tests with standard equipment, that is, with RI/FI meters, signal sources and associated accessories that cover the frequency range from 14 kilocycles to 10,000 megacycles.

Since the mid-and-high frequency tests measure the shielding effectiveness of an enclosure to plane waves, it is possible that one could eventually be eliminated. As experience is gained in taking data of shielding effectiveness of different enclosures it might be found that the deterioration in effectiveness at the lowest natural resonant frequency is essentially invariant for a given type of enclosure. The cell type enclosure made of copper screening usually has a lower shielding effectiveness value at high-frequencies than at mid-frequencies. Therefore, only the high-frequency test might be required for plane wave fields to determine the enclosure capabilities.

V. RECOMMENDATIONS

It is recommended that further work be performed in the area of testing electromagnetic enclosures and the choice of materials used for such enclosures. Suggestions for continued work are given below:

1) For shielded enclosures which are to be operative at the very low frequencies, it is suggested that tests of shielding effectiveness be devised for these very low frequencies, down to approximately 30 cps. Techniques would probaboy be quite similar to those presently being proposed at 15 kc., although much additional information is required on the actual behavior of shielded enclosures at these frequencies. Consequently, it is suggested that

the additional work also include an investigation of the characteristics of various types of commercially available shielded enclosures in this frequency range.

2) Since the proposed low frequency measurement techniques are quite sensitive to defects in shielding junctures, it is proposed that the techniques be used to study the effects of resistance between mating surfaces of shielded enclosures, in order to determine the influence of joint resistance upon shielding effectiveness.

3) In the medium frequency range, it is suggested that improved techniques be devised for performing shielding effectiveness measurements. The present difficulty is that the enclosure acts as a high-Q cavity resonator and, hence, the resonance effects are quite sharp. In order to obtain the required resonance information, it is necessary to tune both the transmitter and receiver used in the measurement simultaneously, a difficult operation because of the sharpness of resonance. Consequently, it is suggested that an improved technique be drived which would permit ganged tuning of a transmitter-receiver combination. Such special test equipment would reduce the time required in order to perform the test of shielding effectiveness and, hence, would reduce the cost for performing such tests.

4) Techniques should be considered for suppressing resonance effects. Possibilities exist for judiciously placing anechoic material in order to accomplish this purpose. A program is suggested in order to devise the proper placement of material and selection of the best material for this purpose. Such a program might also include a general survey of anechoic materials in order to accumulate quantitative engineering data not presently available in useful form.

5) A further research effort might concern the development of a simple and economical source of RF energy for use near nine kmc. For effectiveness measurements at high frequencies, one must now utilize radar equipment for the measurement. Such equipment is unnecessarily complicated, heavy, bulky, and expensive for this purpose. These objections would be overcome with the development of a source intended specifically for the measurement.

6) It is suggested that actual measurement data be obtained on various types of shielded enclosures. The proposed techniques for measuring shielded effectiveness of enclosures should be applied to various types of enclosures of commercial manufacture. Coincidental with such a determination might be the determination of the relative merits of cell-type and isolated-shield enclosures, about which much controversy has raged in the past.

7) It is proposed to obtain additional information of the shielding properties of materials suitable for use in shielded enclosures. This objective can be accomplished partially with the coaxial testing device which was developed under this contract and has been described in previous quarterly reports. The coaxial device contains a lamina of shielding material that extends from the inner to the outer conductor and is perpendicular to their axes. This lamina acts as a barrier to TEM plane waves traveling through the line. Thus, metal sheets, laminated metals, expanded mesh, screening materials, etc., can be tested for shielding effectiveness to plane waves over extended frequency ranges. As a by product of this test, the determination of the electrical properties of these materials, such as permeability and surface conductivity, can be accomplished at various radio

frequencies.

8) In order to enhance understanding of the performance of shielded enclosures, it is suggested that a sound shielding theory for rectangular enclosures be developed. Such work is a difficult theoretical job which would require several years for analysis.

9) Another area of much controversy is that due to the additional shielding effects of multiple shielding layers. Consequently, it is suggested that a study, both theoretical and experimental, be initiated on these effects.

10) A difficulty facing the inexpert user of shielded enclosures is how to select the one best suited for his use. For this purpose, it is suggested that an instruction booklet be prepared for users on the subject "How to Select a Shielded Enclosure".

11) A final suggestion is to investigate the use of lightweight materials for shielding applications. Aluminum has potential value as a shielding material provided proper junctures between sheets can be effected. Furthermore, the use of sandwich-type material might be investigated, such as thin copper or aluminum sheets separated by a fibered honeycomb material. New lightweight materials for reducing reflections inside enclosures should also be evaluated.

It is hoped that some of the above suggestions will be found useful in helping to advance the state of the shielding art.

Respectfully submitted,

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